Kissimmee Watershed Planning and Operations Project

Model Evaluation for MODHMS

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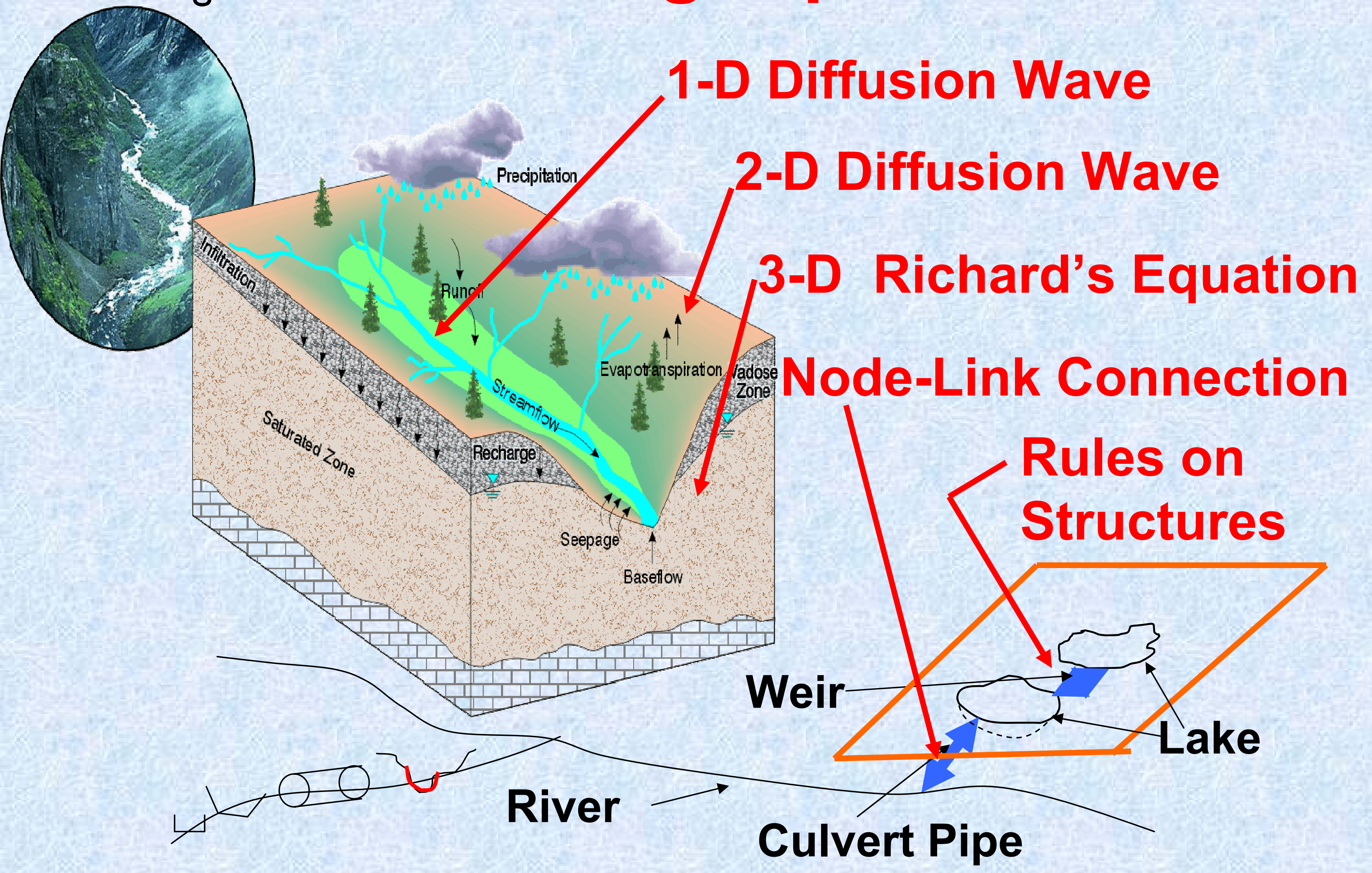
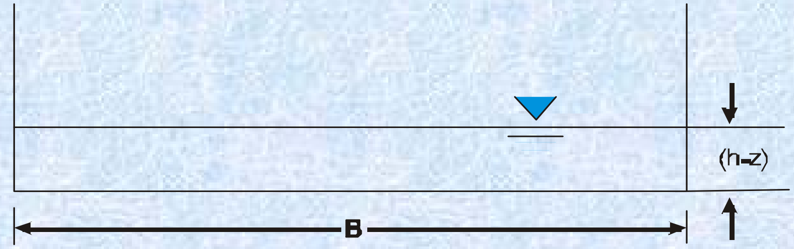
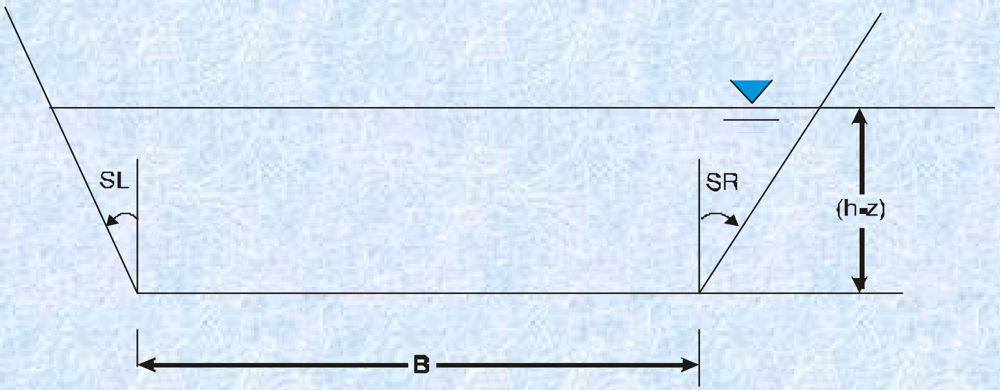
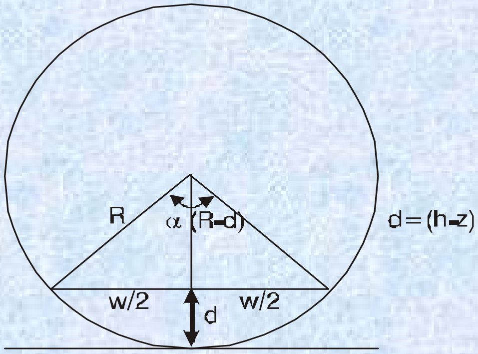
Governing Equations



Special Channel Section Types







Priesmann slot concept for pressurized flow

Hydraulic Structures Simulation Capability

CULVERTS:

Designs:

- Box
- Pipe
- Embedded
- Countersunk
- With Weirs/baffles
- Arrayed
- Inlet/Outlet drops

GATES:

WEIRS:

Designs:

- Rectangular
- Triangular
- Notched
- Finger Weirs

REGULATING STRUCTURES:

Q = Q (t)

Q = f (distant flow)

Q = f (distant head)

Pump Stations

Other Structures

Hydraulic Structure Computation

General hydraulic structure computational schemes are provided by supplying various stage-discharge relations (observed or computed):

Q is a function of h_{ups}

Q is a function of h_1, h_2

Q is a function of h_{ups}, h_{dns}

$Q = Q_1 + Q_2$ where

$Q_1 = f(h_1)$ and $Q_2 = f(h_2)$

Need tabular values of h_1, $(h_1 - h_2)$, and Q to ensure that Q = 0 when $h_1 = h_2$.

Flux	H1 = 1	H1 = 5	H1 = 10
H2 = 0	10	50	100
H2 = 1	0	30	70
H2 = 2	-10	10	40

For H1 = 1 and H2 = 1, the flux is zero

For H1 =2 and H2 = 2, the flux is -5

For H1 = 1.5 and H2 = 1.5, the flux is -1.875

Regulation of Structures

- Unregulated and regulated structures can be present in a simulation
- Unregulated structures are always on
- Regulated structures are operated according to a set of rules
- Two types of rules
  - Operation Rules
  - Shift-work Rules

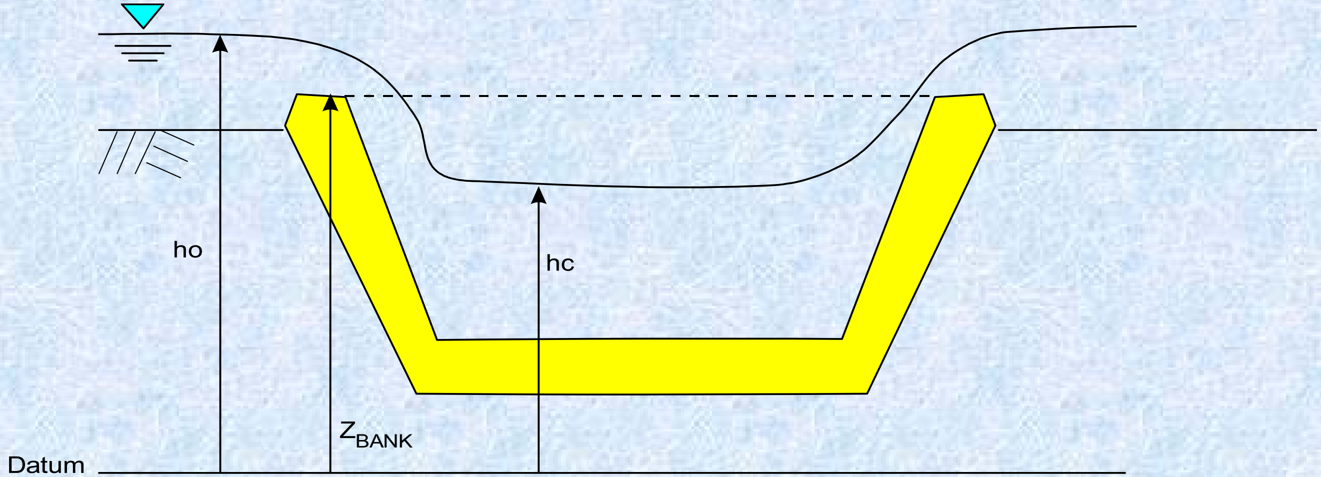
Operation Rules

- A structure may OPEN / CLOSE if the HEAD / FLUX at a trigger location (in GW, OLF, or CHF domain) is ABOVE / BELOW a trigger value and within times (T_start, T_end).
- A two-way trigger: If structure opens above a trigger value, it also closes below trigger value.
- Structure subject to a maximum flow rate
- Multiple (independent or dependent) rules for operating a structure
- Trigger subject to relative difference between heads or flows at two locations

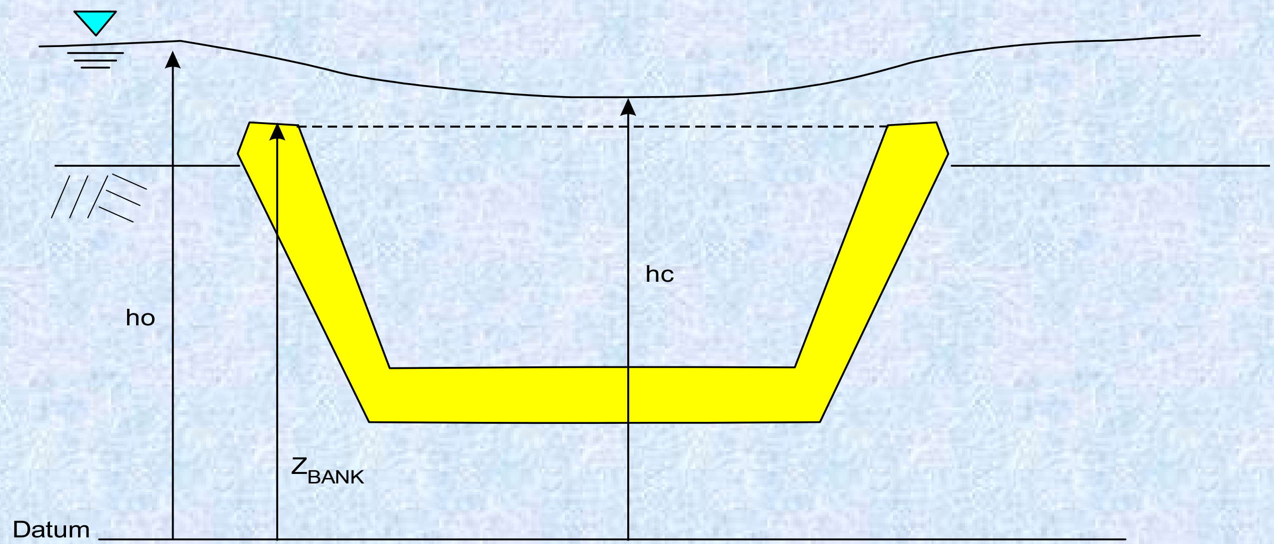
Shift-work Rules

- During a cyclic period (24 hours), shift-work occurs between T_start_shift (9 hours) and T_end_shift (18 hours) when within times (T_start, T_end).
- Structure is operated only during period of shift-work.
- Two options when outside of shift period
  - Structure is always off outside of shift period
  - Structure is maintained in it's on/off state outside of shift period

Channel - Overland Flow Interaction

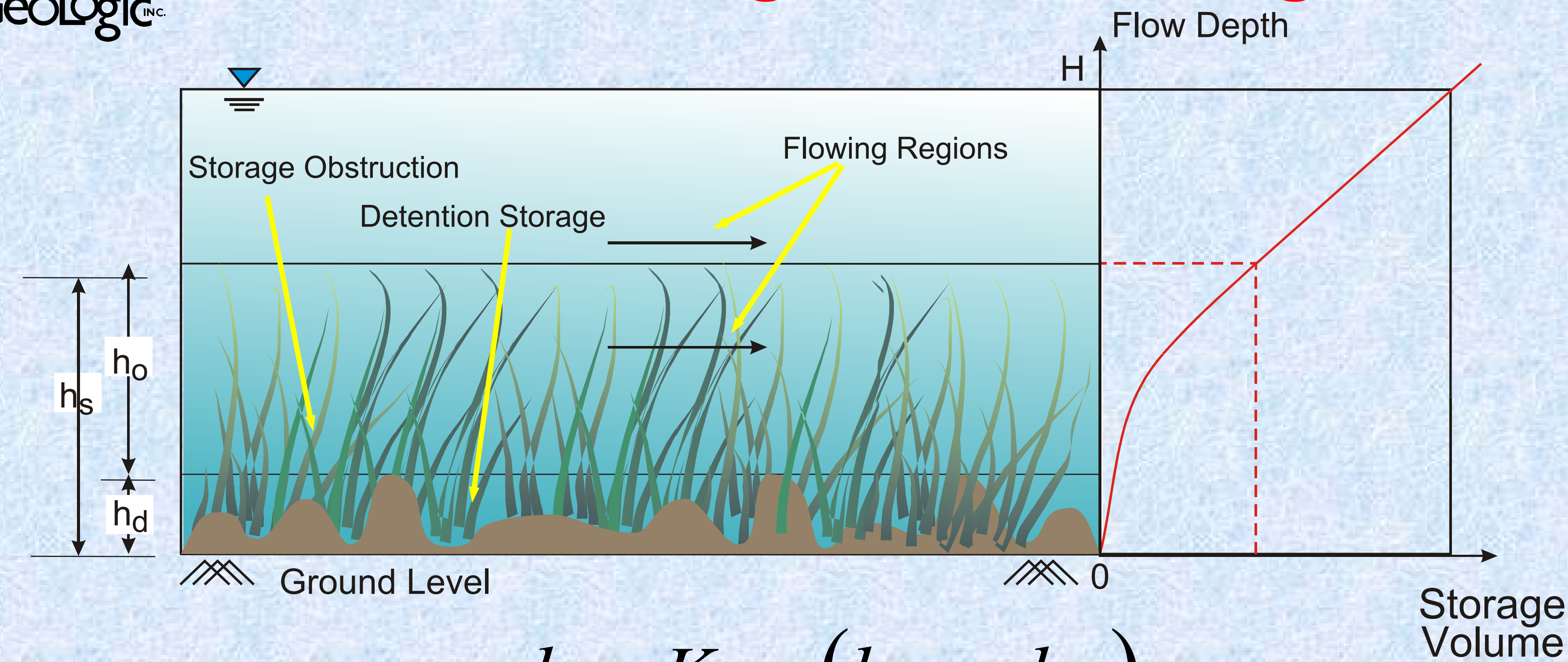


Free flowing weir, hc < Z_{BANK}



Submerged weir, hc > Z_{BANK}

Surface Storage and Exchange Terms



$$q_{go} = k_{rgo} K_{GO} \left(h_G - h_o \right)$$

- $k_{rgo}(h_{ups}) = 0$ at land surface; 1 at top of rills
- Horizontal flow above height h_d
- Horizontal flow obstruction option

Groundwater Interaction Fluxes

Overland - Groundwater flow

$$q_{gO} = k_{rgO} K_{GO} (h_G - h_O) = Q_{gO} / (\Delta x \Delta y)$$

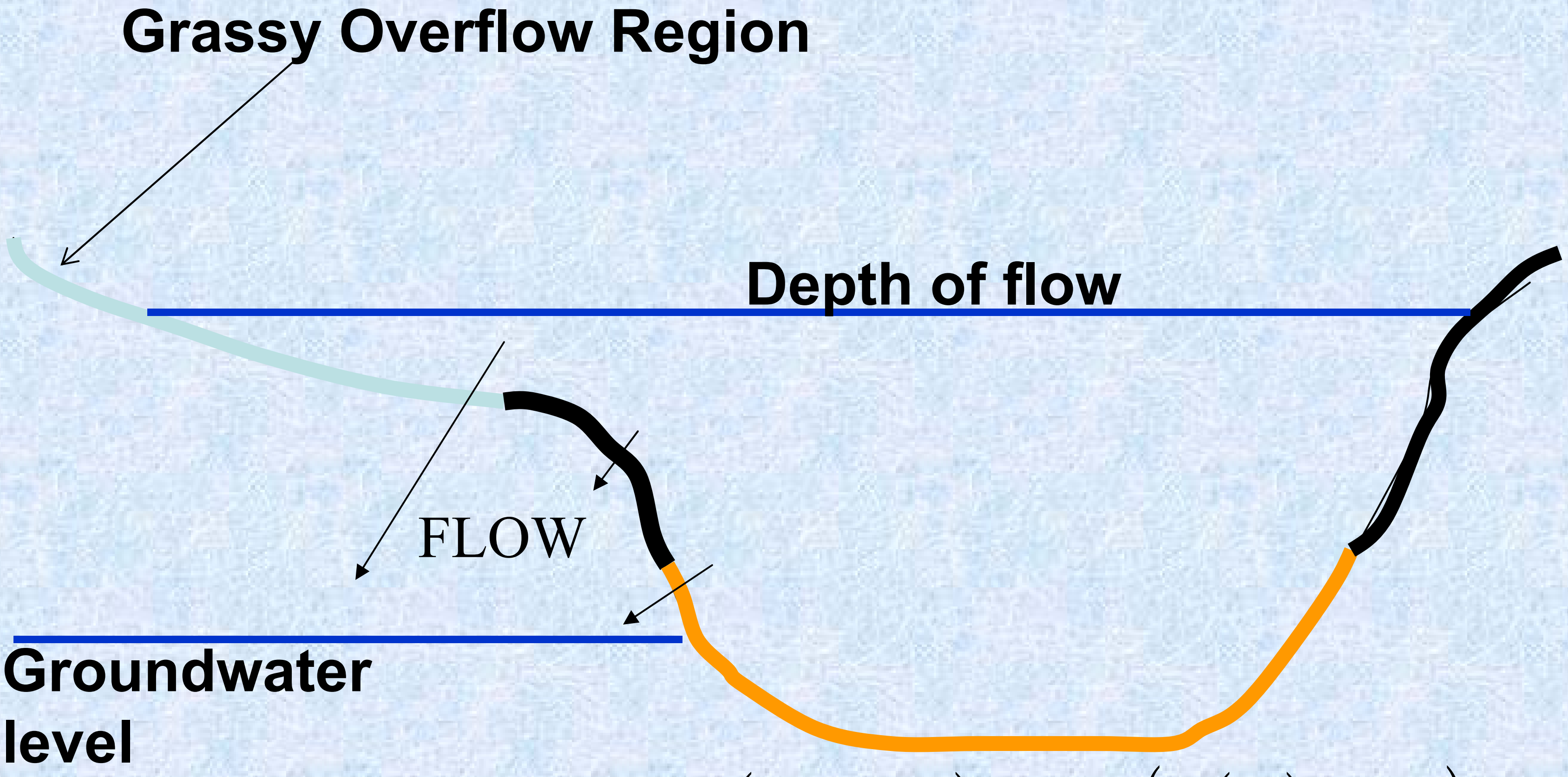
Channel - Groundwater flow

$$q_{gC} = k_{rgC} K_{GC} (h_G - h_C) = Q_{gC} / L P_{ups}$$

where K_{GC} may be a constant or vary with flow depth. For varying K_{GC} with conductivity K_1 to depth d_1 etc.

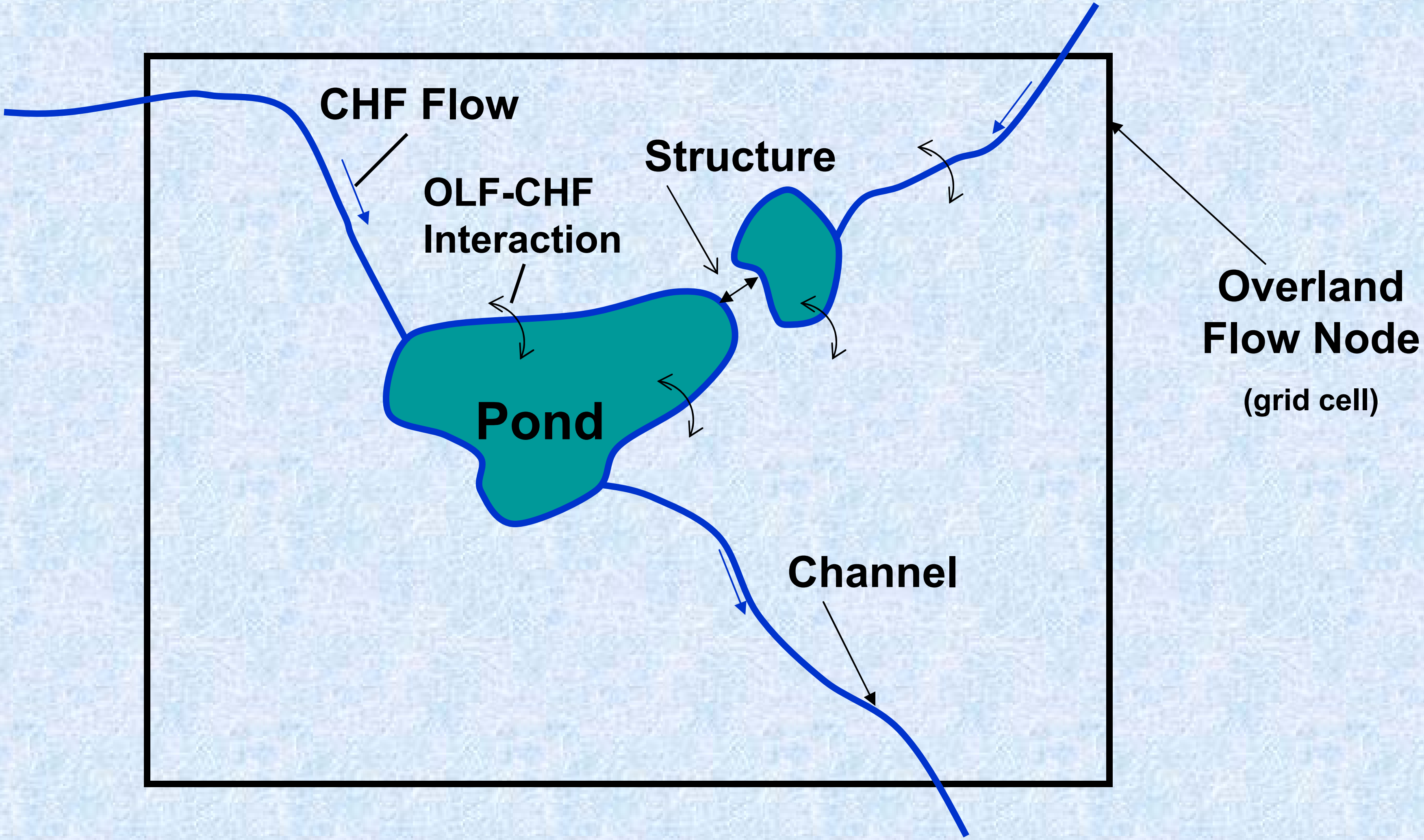
$$K_{eff}(Y_1) = \frac{K_1 P_1 + K_2 (P_2 - P_1) + K_3 (P(Y_1) - P_2)}{P(Y_1)}$$

Leakance varying with depth of flow within Channel Section



$$K_{eff}\left(Y_1\right) = \frac{K_1\ P_1 + K_2\left(P_2 - P_1\right) + K_3\left(P\left(Y_1\right) - P_2\right)}{P\left(Y_1\right)}$$

Small Surface Water Bodies



Small Surface-Water Bodies

- A channel node represents a surface-water body
- Tabular stage-area relationship for the surface-water body provides:
  - Storage term computation
  - Area over which groundwater connection occurs
  - Effective leakance computation for varying leakance with flow-depth
- Perimeter of surface-water body provides length over which overland connection occurs
- Direct connection to channel node
- Connection to other surface-water body via a structure

Direct Flow Links between Nodes

- Connect isolated parts of a domain using a variety of Q-h relationships
- Links can be made between any nodal component (GW, OLF, CHF, and stage-storage nodes)
- A structure formula provides flow in the link (various tabulated Q-h relationships)
- Channel flow equations and all cross-section types also included for links (with storage and OLF / GW interactions)

Other Hydrologic Components

- Interception Storage (bucket model)
- Evapotranspiration
  - **Physics based and Parametric options**
  - **PET may be input or calculated. Calculated methods include:**
    - **Bare Ground (Senarath et al., WRR 36,3, 2000)**
    - **Vegetated Surfaces (Penman Montieth)**
- Infiltration formulas – Kostiakov; Green Ampt; GSVE
- All water features and boundary conditions available in MODFLOW – HFB, FHB, CHD, GHB,OBS extended to OLF and CHF domains
- Recharge Time-Series (RTS) for short-term events
- Reactive Transport capability for all domains

Interception & Evapotranspiration

- **Bucket Model for Interception**
  - Interception storage = f (LAI)
  - Recharge to ground after interception is full
  - ET_{ref} first met from interception storage
  - Remaining ET from transpiration & evaporation
- **Physics-based Evapotranspiration varies with:**
  - LAI (transient input)
  - Moisture Content (state variable)
  - Root Zone Distribution Function / Evaporation Distribution Function (transient input)
- **Parameteric Evapotranspiration**
  - ET flux varies with depth to water table

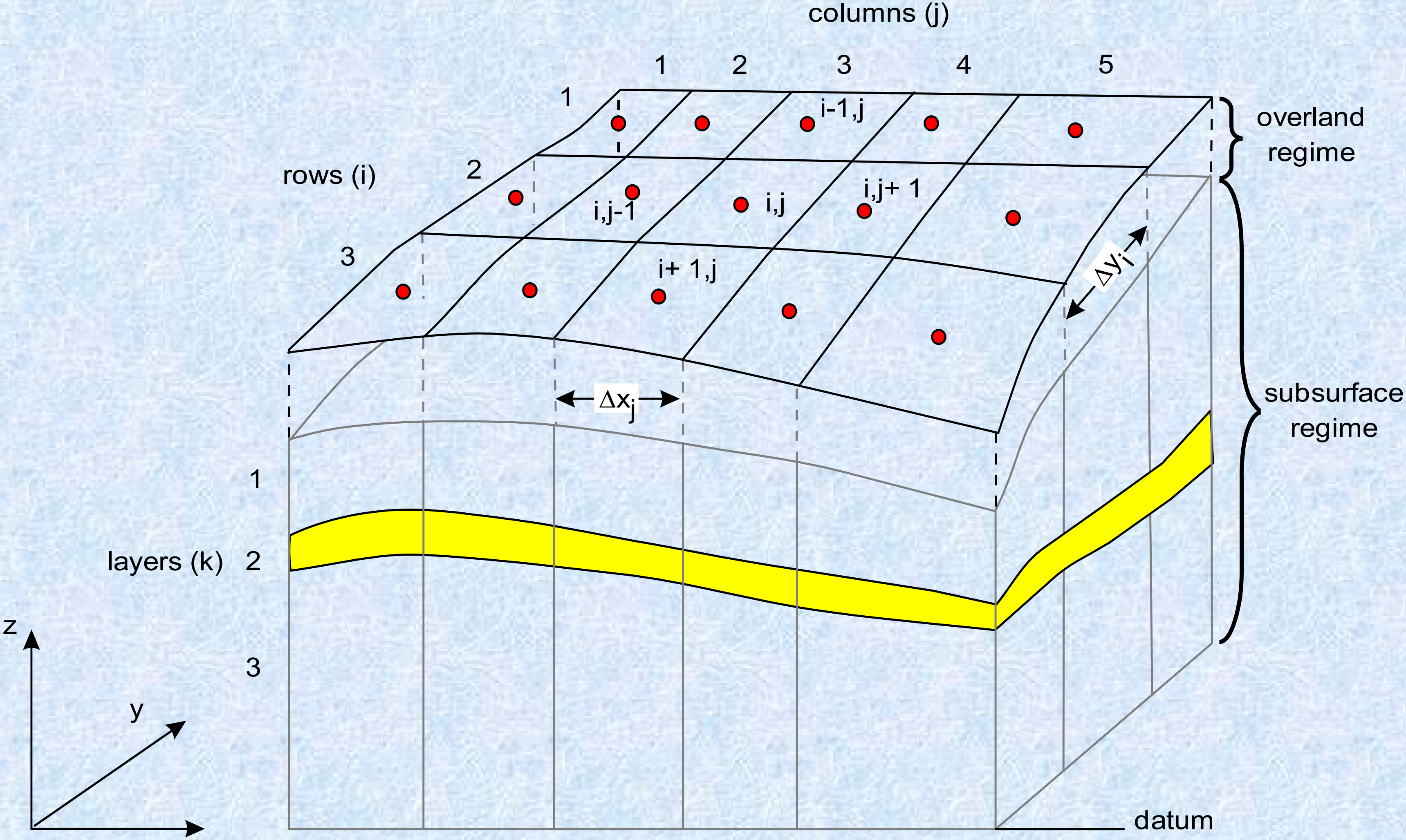
Adaptive Time-Stepping

- For short-term events, utilize refined computational time steps adapted to lie exactly at start and end times of rainfall events (and optionally for rule changes)
- Within hiatus periods, time-step sizes increase depending on problem non-linearity
- Time steps also adapted to accommodate printing times supplied by user
- Averaged hyetographs may be provided for long-term simulations
- Option for restart at non-zero relative time

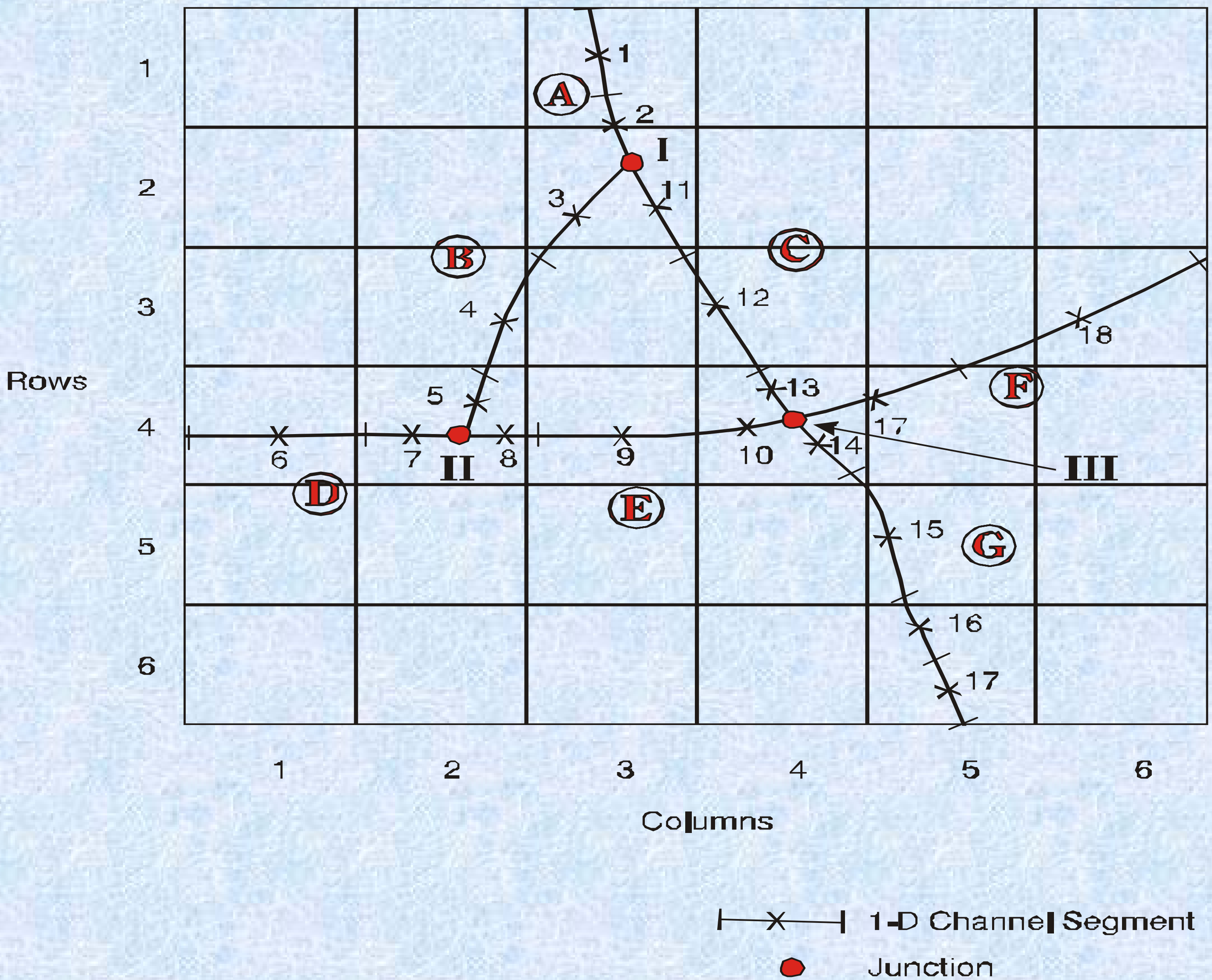
Time-varying Conditions

- At every stress period, the following may vary:
  - Boundary stresses
  - Evaporation rate
  - Friction coefficients along flow direction(s) for CHF /OLF
  - Rill height
  - Obstruction storage height
  - Reference ET input - or calculation parameters
    - Air density; atmospheric pressure; saturated vapor pressure; relative humidity; wind speed; temperature; radiation and soil heat adsorption; mean crop height; Monteith Canopy resistance parameters;
  - Leaf Area Index
  - Coefficients C1, C2, C3 for actual ET
  - Root zone distribution function
  - Crop Coefficient

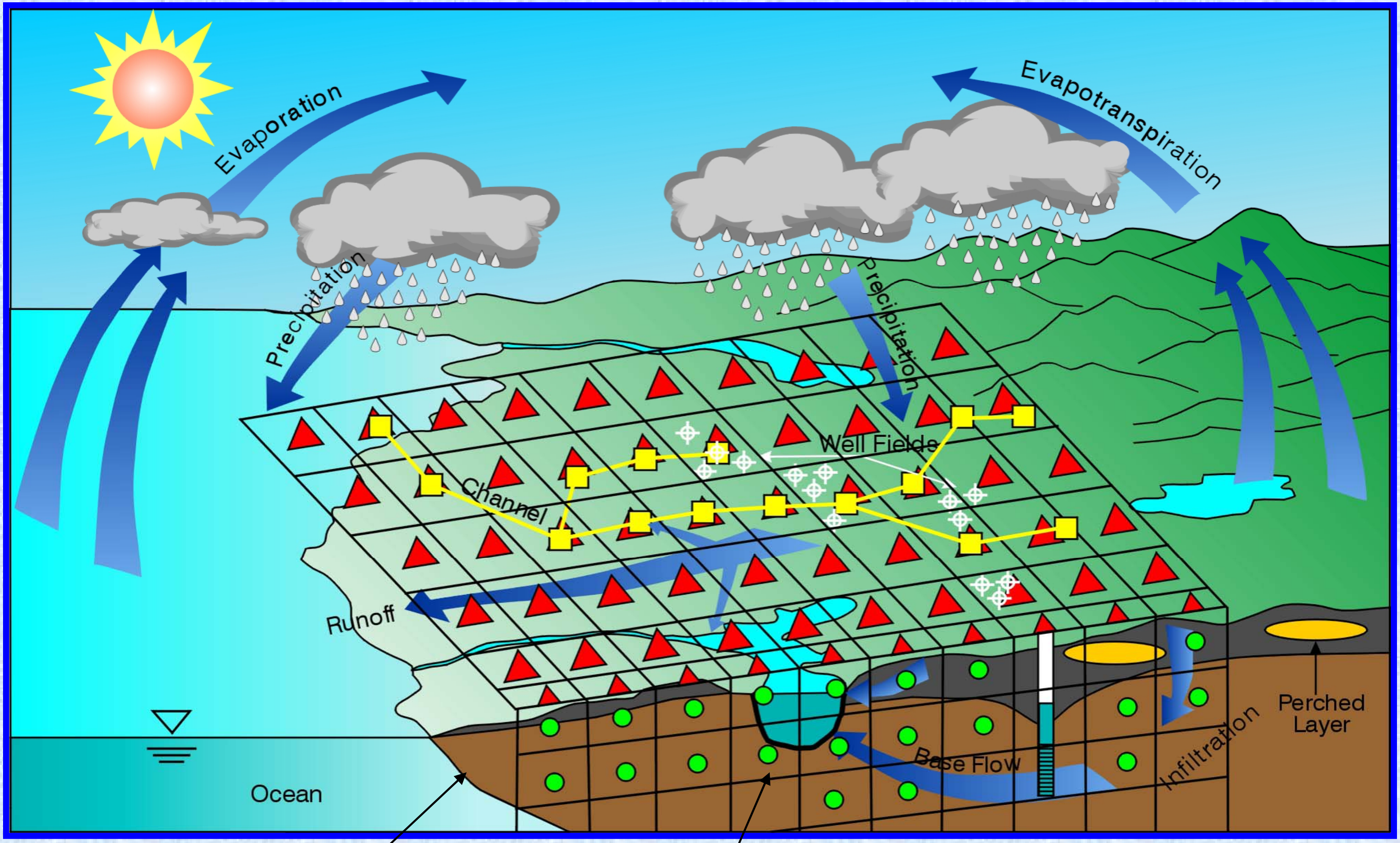
Discretization – Rectangular or Curvilinear Finite-Difference



Channel/Pipe Discretization – Finite Volume



Holistic Solution for Hydrologic Cycle



Saltwater/Fresh Water Interface

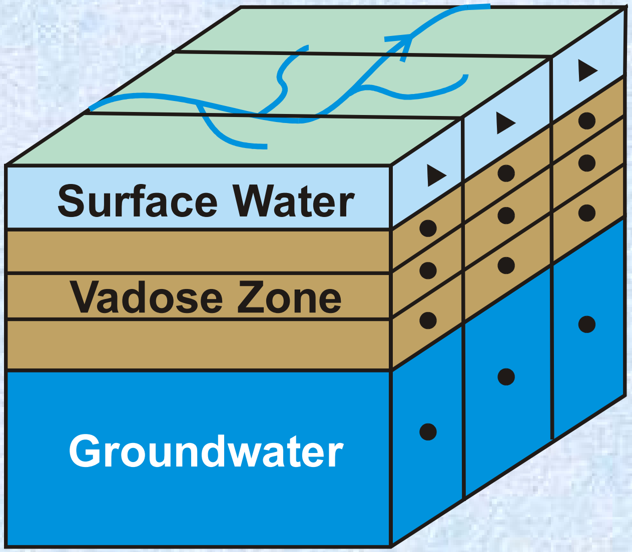
In-ground Reservoir

Numerical Schemes

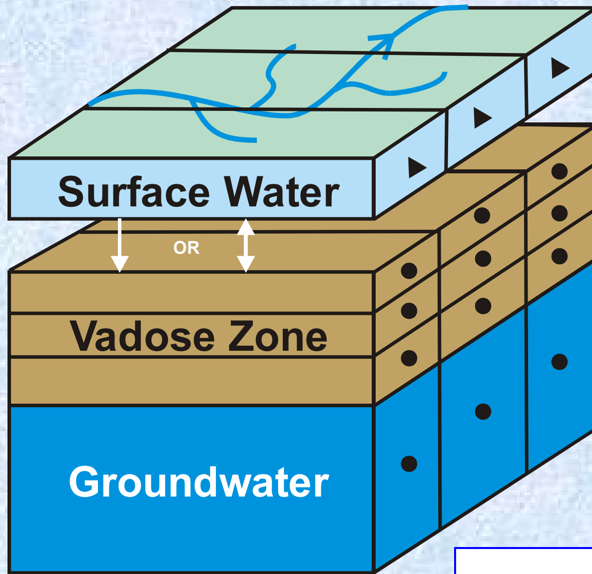
- Fully implicit, fully coupled solution with options for linked schemes
- Newton-Raphson Linearization available in addition to Picard option
- Unstructured Matrix Storage Scheme
- Orthomin, GMRES, BiCGSTAB Solution Schemes
- Adaptive Time-Stepping & Output Control
- Flexibility of conceptualization
  - **Parametric or Physics Based ET**
  - **Kostiakoff, Green Ampt, Richards Equation, GSVE**
  - **Mix-and-match of GW, OLF, CHF domains and boundary conditions**
  - **Node-Link method for conceptual models**

Conjunctive Flow Solution Schemes

Fully Coupled Solution:



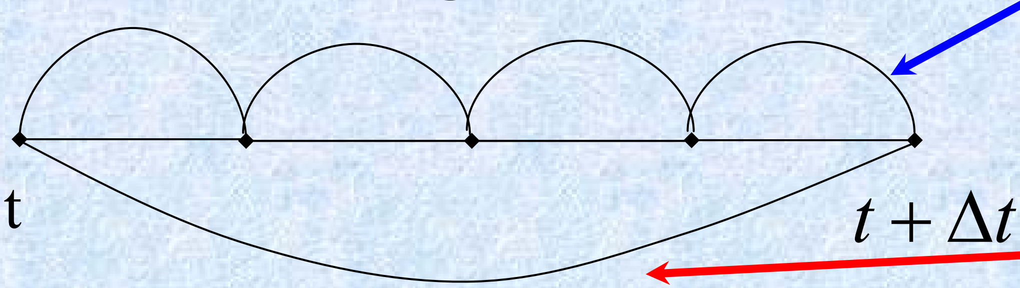
Linked Solution:



- Non-iterative
- Iterative

Coupling of Flux or Head at the Interface

Time Stepping:



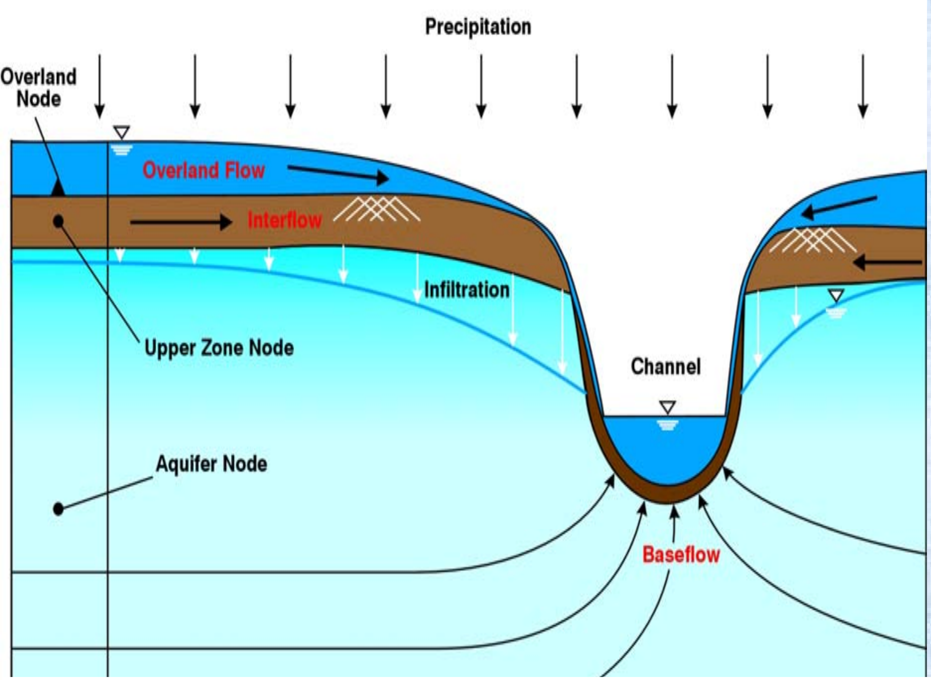
Time steps for the surface water domain

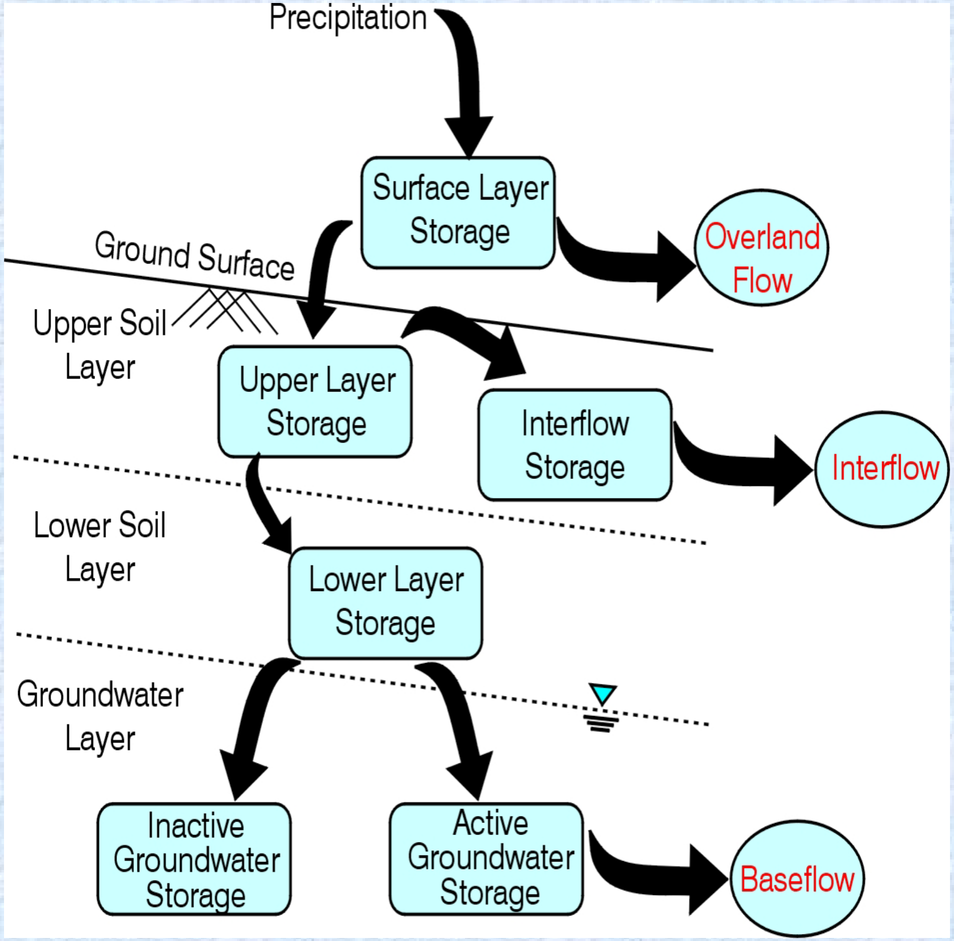
Time steps for the subsurface domain

Comparison of Fully Coupled and Linked Schemes

- Fairbanks, et al., Comparison of Linked and Fully Coupled Approaches to Simulating Conjunctive Surface / Subsurface Flow and their Interactions – MODFLOW 2001 Conference
- Panday, Multi-Scale Conjunctive Modeling of Surface and Subsurface Flow – MODFLOW 2003 Conference
- Linked approaches give good results only for “small” time-steps

Our Three-Layer Model Conceptualization	Classical Conceptualization of HSPF (after Ford & Hamilton, 1996)





Salient Features:

- **Effective for regional and sub-regional applications**
- **Accounts for all components of the hydrograph including interflow**
- **Accurately track soil moisture storage, infiltration, and water table position**

Pre- and Post-Processing

- ViewHMS provides complete pre- and post-processing capabilities
  - **Create / modify grids, assign properties and boundary conditions manually or automatically**
  - **Import Shape-Files with various interpolation options to parameterize spatially varying properties**
  - **Query Access Databases for hydraulics**
  - **Manipulate input and output data for calibration, and calibration statistics**
  - **Read model output files for viewing / export to Tecplot, Surfer/Grapher, ArcGIS, Maya, Modflow Binary**

Pre- and Post-Processing - Continued

- ArcHMS plug-in for ArcGIS provides direct interface of ArcGIS to model files
- Subsurface setup in any MODFLOW processor
- Fully documented ASCII input files allow manual editing for minor changes, QA, or user development of pre-processing utilities
- Standard ASCII and binary output files based on MODFLOW format. This allows user development of customized post-processing utilities for interfacing with software of choice

Summary of Model Formulation

- Basin Hydrology – 2-D spatially distributed
- Initial abstractions – Detention storage; Infiltration; Interception; ET
- Infiltration options – GSVE; Richards Equation; analytic infiltration formulas
- SW-GW Interaction – Holistic; fully coupled; mass conserved (adaptive time-steps); drying of rills provides converged solutions
- GW interactions between sub-basins – Solves GW flow rigorously
- Detention Storage – Estimated for rills; Includes obstruction storage exclusion

Summary of Model Formulation - Continued

- Runoff generation – Diffusive wave; User defined (tabulated) Q-h (or Q-h1h2) via Node-Link method
- Hydrologic routing – Holistic, physics-based, spatially-distributed; Node-Link method
- Hydraulic routing – Various canal cross-sections; Node-Link method
- Hydraulic structures – Various options of tabulated input (ViewHMS provides formulas)
- Structure operations – Comprehensive
- Screening mode – Flexible domain options; Node-Link method; infiltration options; ET options; adaptable boundary conditions

Summary of Model Formulation - Continued

- Groundwater hydraulics
  - Finite-difference / Finite-volume combination; Rectangular / Curvilinear Grids
  - Quasi-3D and fully 3-D setups within the same simulation
  - Saturated / unsaturated zone solved fully 3-D holistically
- Adaptive time-stepping to assure convergence within and among all domains
- Flexibility of formulations and boundary conditions to suit problem objectives and available data
- Holistic hydrologic cycle simulation with linked alternatives in an adaptive time-stepping framework

Specifics of SW-GW Interaction Implementation

- Linkage between GW and SW grids: canals, wetlands, sub-basins, infiltration, exfiltration etc. – Fully coupled: GW and SW interaction based on Darcy’s Law; SW interactions based on weir equations
- Features at a smaller scale than model grid – Finite-Volume connectivity; node-link approach
- Secondary or Tertiary Canals Interaction with GW – Holistic, physics-based interactions between all connectivities
- Reservoir Routing and hydraulic routing problems at C&SF structures – Includes high level of complexity

Flood Routing Problems of Kissimmee Basin

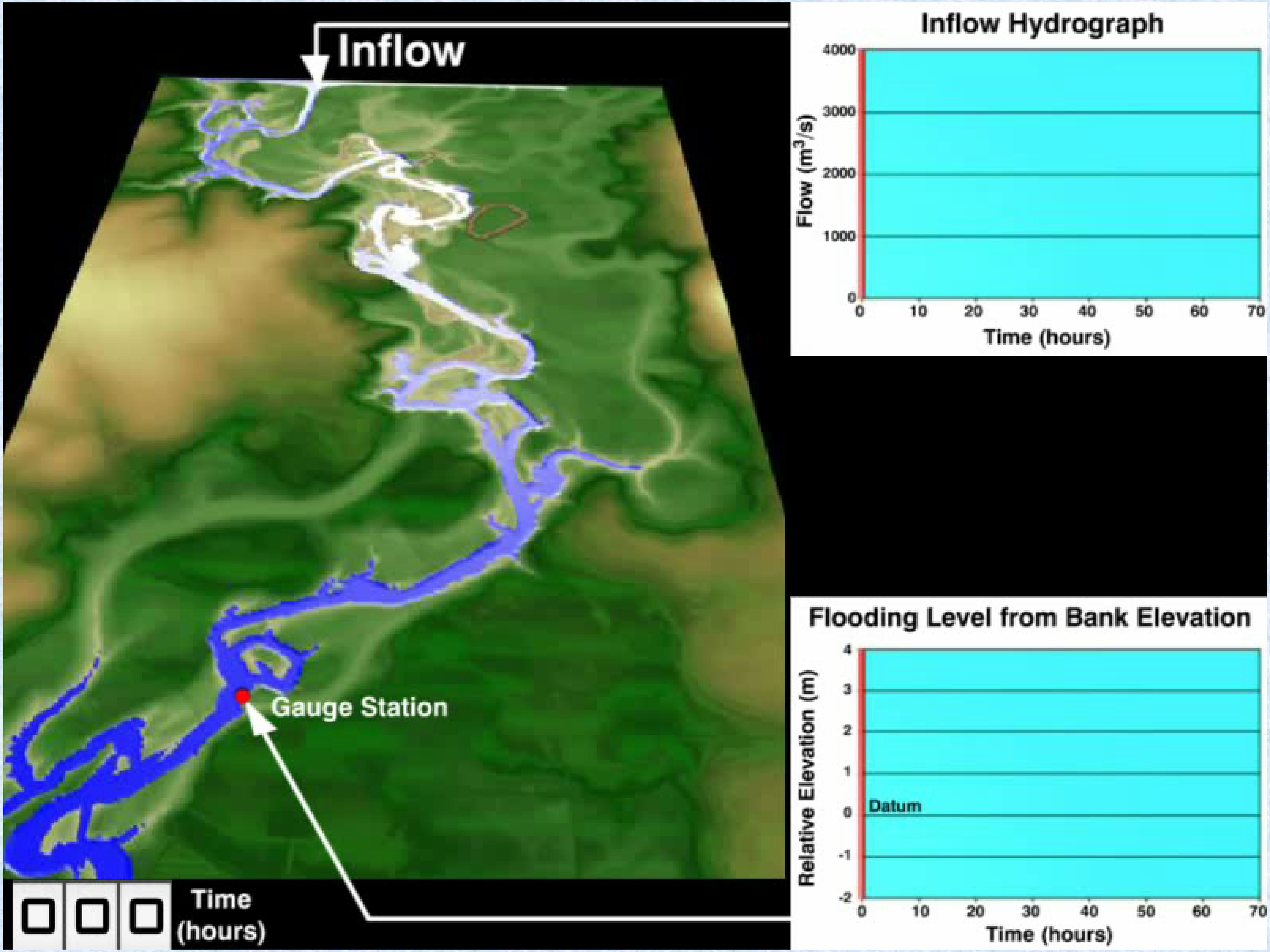
- Characterize regional hydrology, calculate lake stages, river flows, discharge from KB into Lake Okeechobee, effects of water control structure operations, impacts of Floridan Aquifer pumping – Holistic, comprehensive and rigorous SW_GW modeling capability with structures and operations
- Long term simulation (20 to 30 years) and flood event simulation (days) – Adaptive time stepping
- Local and regional levels of resolution – multi-scale features; node-link approach

Flood Routing Problems of Kissimmee Basin – continued

- Address Uncontrolled / Controlled and Free / Submerged combinations of gate opening and tailwater submergence – Combinations of Structures and Operations
- Incorporate effects of urbanization trends – Temporal input of land use related properties, canal properties, or canal existence
- Address phosphorous reduction strategies – Comprehensive reactive transport simulation capabilities

Flood Routing Problems of Kissimmee Basin – continued

- Perform screening level investigations – Flexibility to suit problem and available data
- Comprehend results and convey them to reviewers, stakeholders and decision makers – Output can be processed for a variety of tools for analysis and visualization


Inflow
Gauge Station
Time
(hours)
Inflow Hydrograph
Flow (m³/s)
4000
3000
2000
1000
0
0
10
20
30
40
50
60
70
Time (hours)
Flooding Level from Bank Elevation
Relative Elevation (m)
4
3
2
1
0
-1
-2
Datum
0
10
20
30
40
50
60
70
Time (hours)

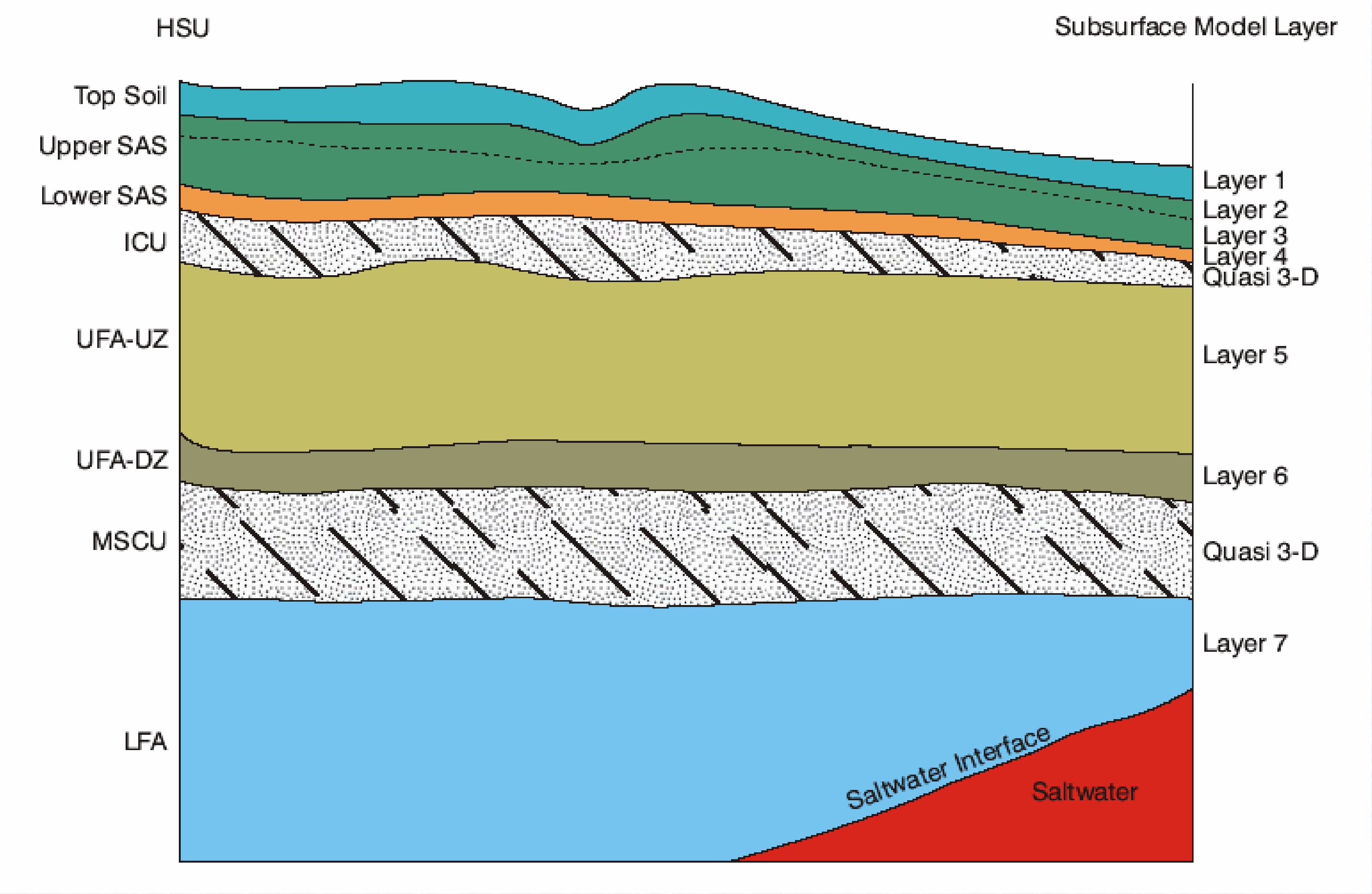
MODHMS Application Example – WOSC-ISGM around Orlando, Florida

- Regional ECF groundwater flow model – Used for Water Supply Permitting
- Surface-water features are inter-connected or internally drained – Highly Engineered System
- Conjunctive model was needed to assess overall water management, recharge, and impact of FAS withdrawals on surface water bodies
- ECF groundwater model was conceptualized via lumped estimates of hydrologic cycle components

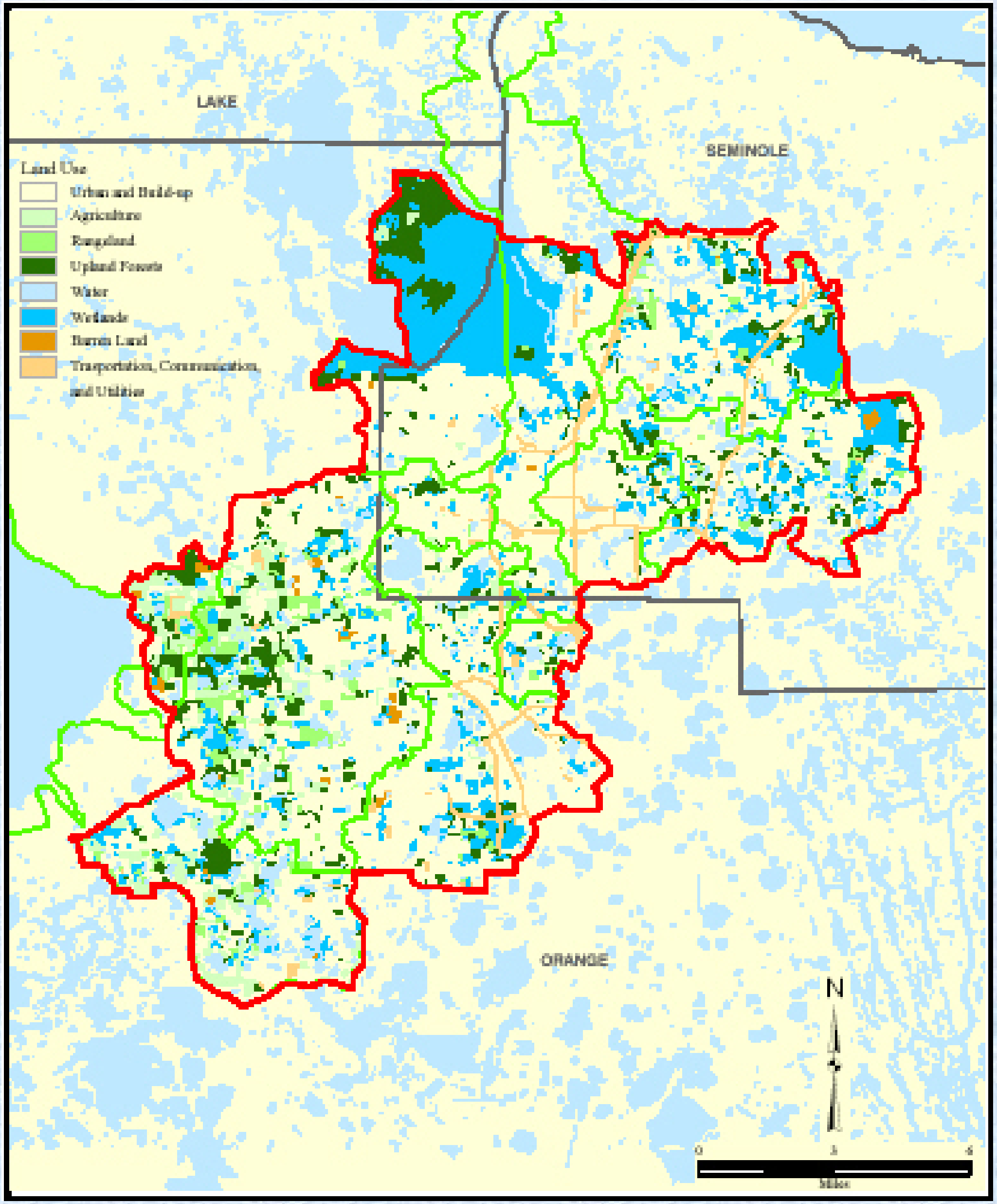
WOSC-ISGM Setup and approach

- WOSC-ISGM expands on flow model conceptualization of ECF model
- Telescope from regional ECF model and include complexities of SAS, surface hydrology & hydraulics
- Grid-size 625 ft areally
- Around 180,000 active nodes
- Model includes 3-D unsaturated zone, physics-based ET, detailed hydraulics and drainage wells (node-link)
- Model implementation performed in 18 months

Subsurface Conceptualization



Model domain and parameterization

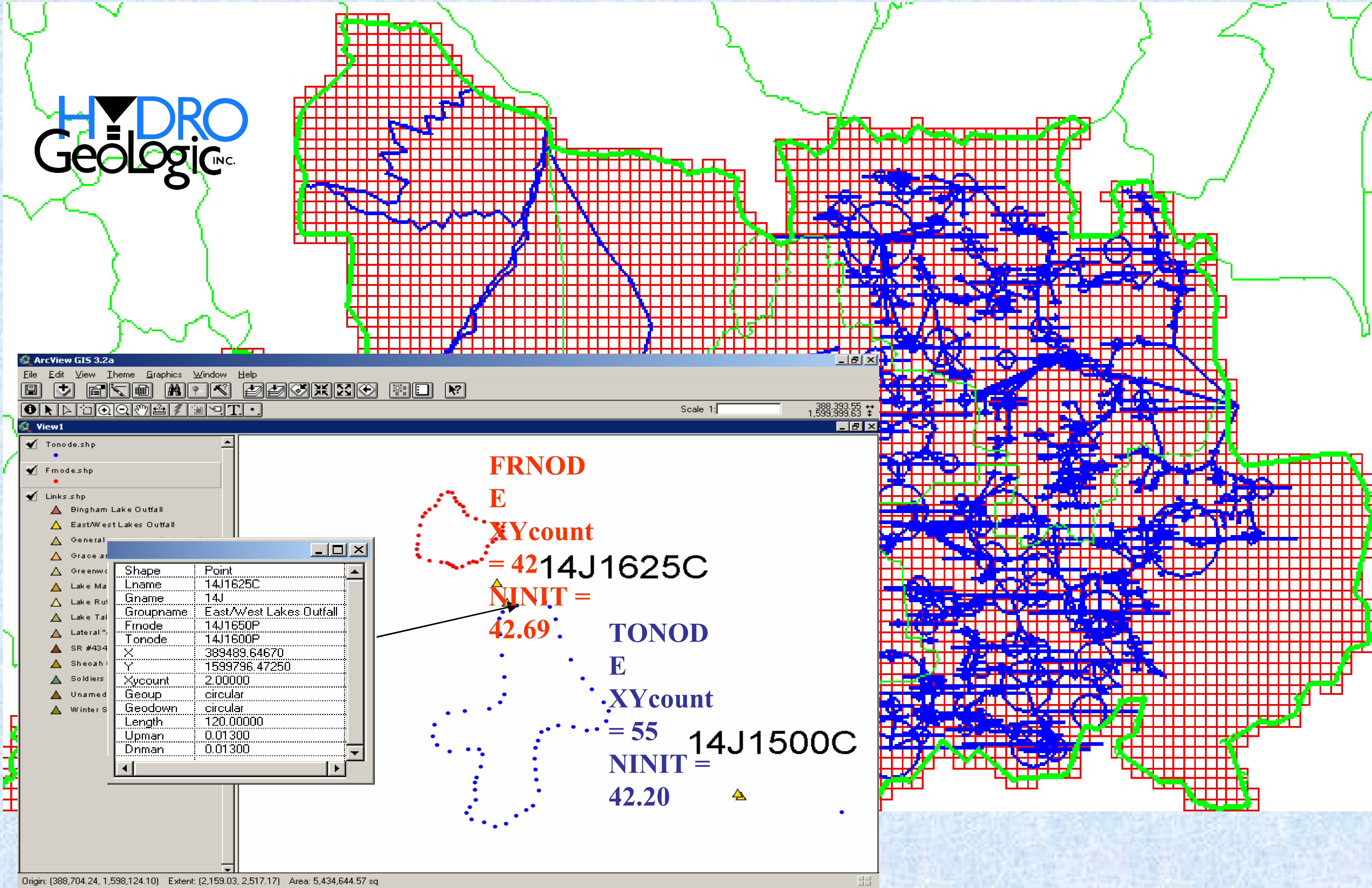


- **Land-Use / Land Cover:** LAI, friction, RDFI, EDFI, Surface Leakance
- **Soils Data:** Moisture retention, porosity, conductivity, field-capacity and wilting-point saturations

Other Parameterization and Input

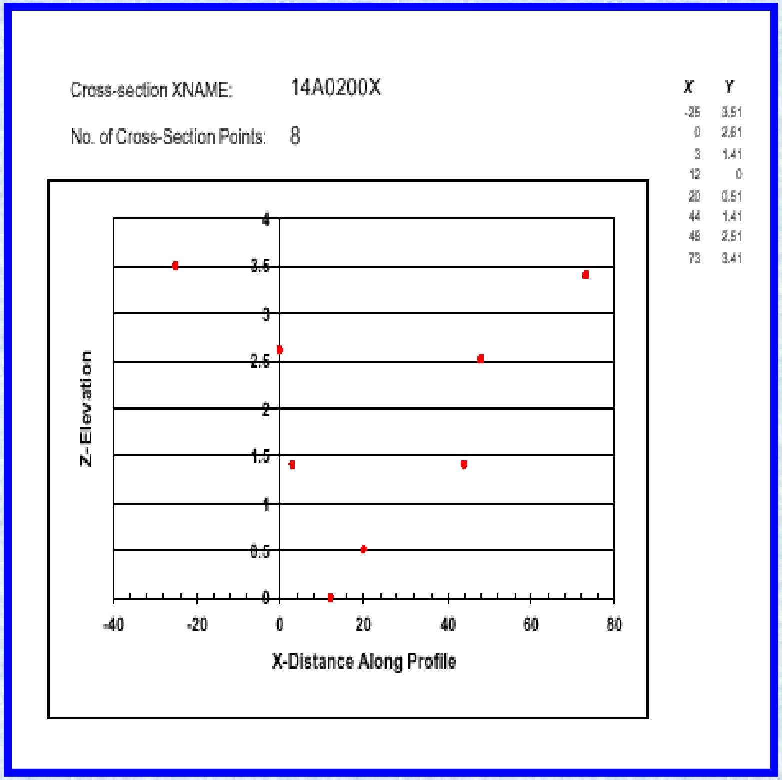
- **Geology and Stratigraphy:** Aquifer characterization
- **DEM:** Surface elevation
- **Hydrology Databases:** Drainage system geometry, connectivity and characteristics, Surface-water body features, and Structure characteristics and operations
- **NEXRAD data:** Precipitation
- **Well permitting databases:** Withdrawal estimates
- **Various GIS coverages:** Local water budget components, agricultural or septic water returns, domestic well withdrawals, Land-Use changes, etc.

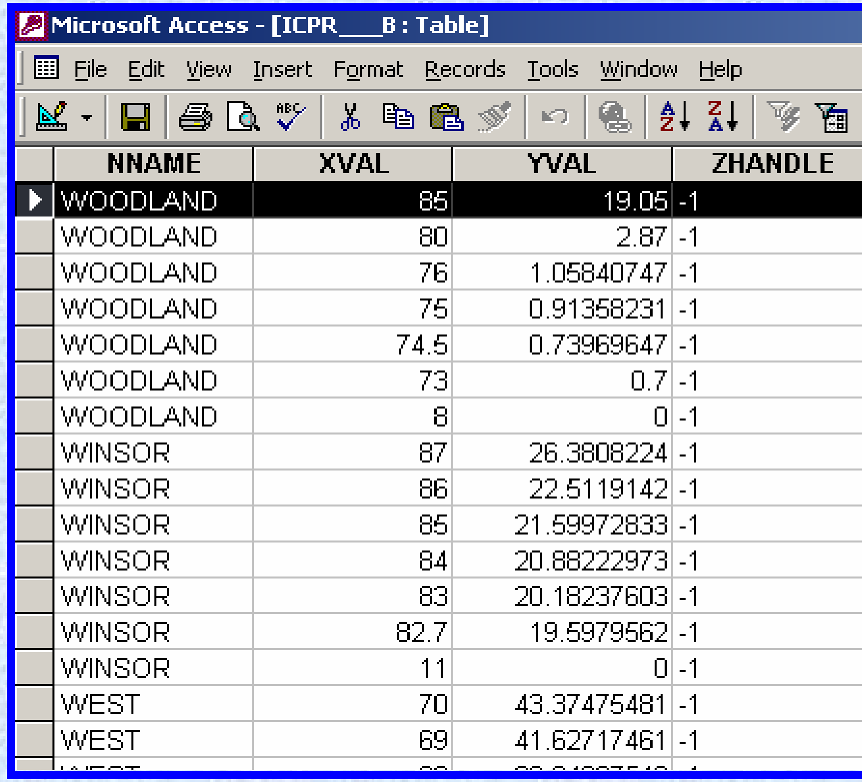
Hydrology from ICPR databases



Channel Geometry

Stage-Area Relations





Microsoft Access - [ICPR___B : Table]

File Edit View Insert Format Records Tools Window Help

NNAME	XVAL	YVAL	ZHANDLE
WOODLAND	85	19.05	-1
WOODLAND	80	2.87	-1
WOODLAND	76	1.05840747	-1
WOODLAND	75	0.91358231	-1
WOODLAND	74.5	0.73969647	-1
WOODLAND	73	0.7	-1
WOODLAND	8	0	-1
WINSOR	87	26.3808224	-1
WINSOR	86	22.5119142	-1
WINSOR	85	21.59972833	-1
WINSOR	84	20.88222973	-1
WINSOR	83	20.18237603	-1
WINSOR	82.7	19.5979562	-1
WINSOR	11	0	-1
WEST	70	43.37475481	-1
WEST	69	41.62717461	-1

The model was assembled and calibrated to average 1995 conditions and to transient conditions from June 1995 through September 1999 (June 1997 onwards used for verification)

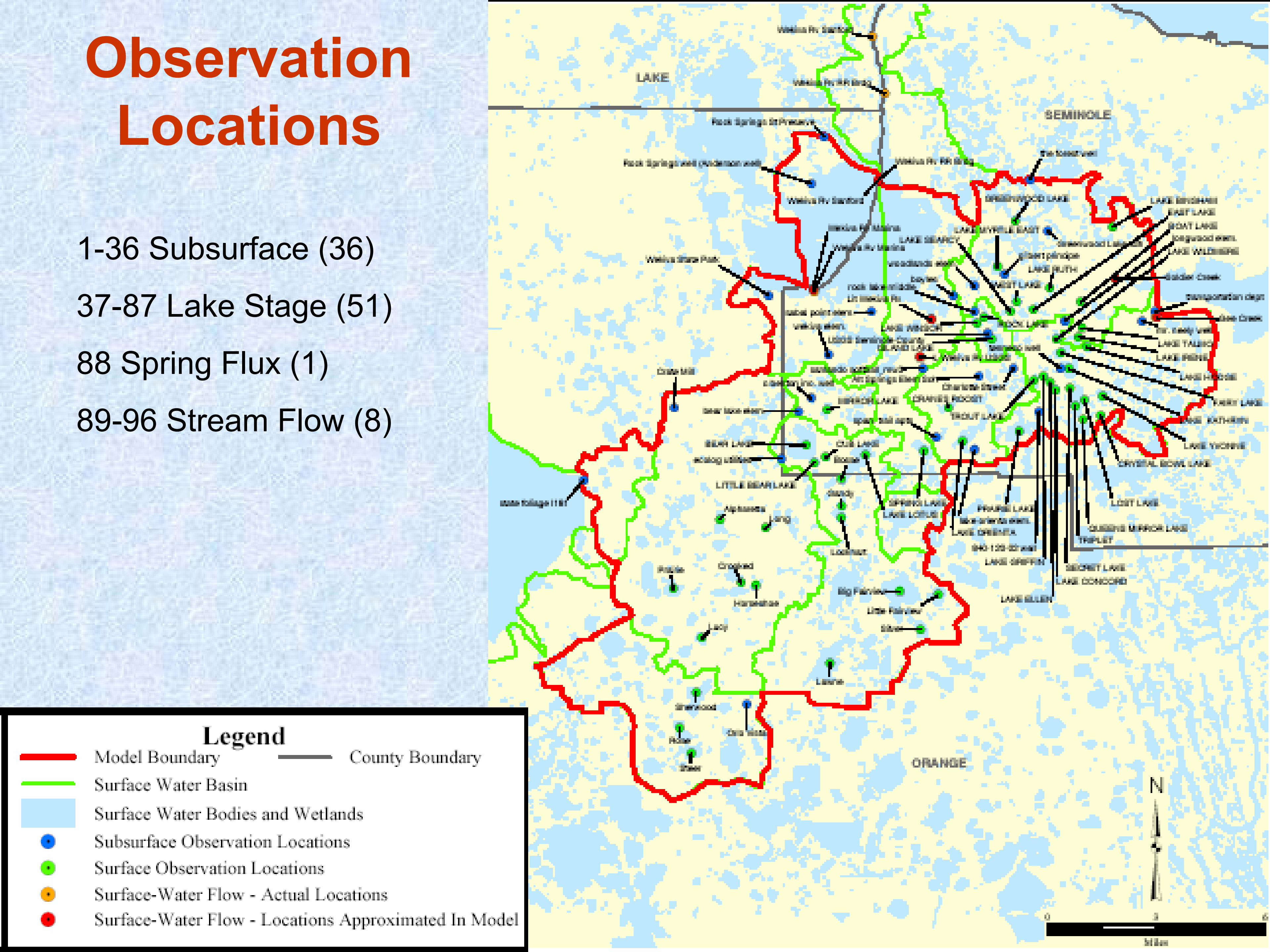
Observation Locations

1-36 Subsurface (36)

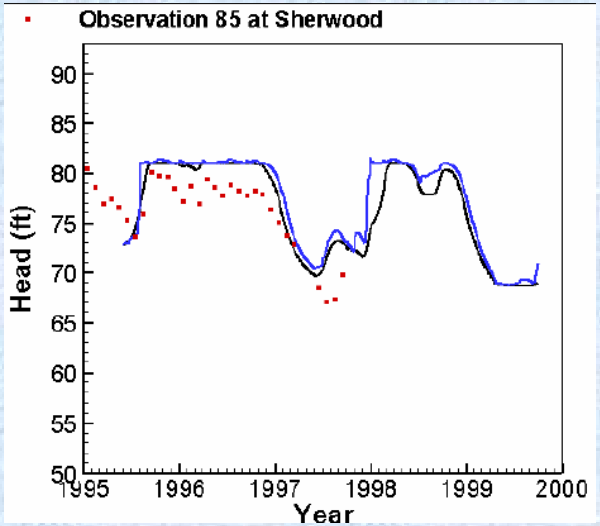
37-87 Lake Stage (51)

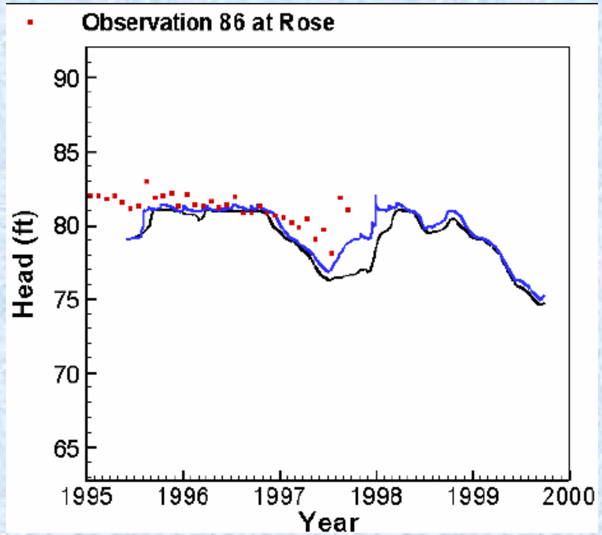
88 Spring Flux (1)

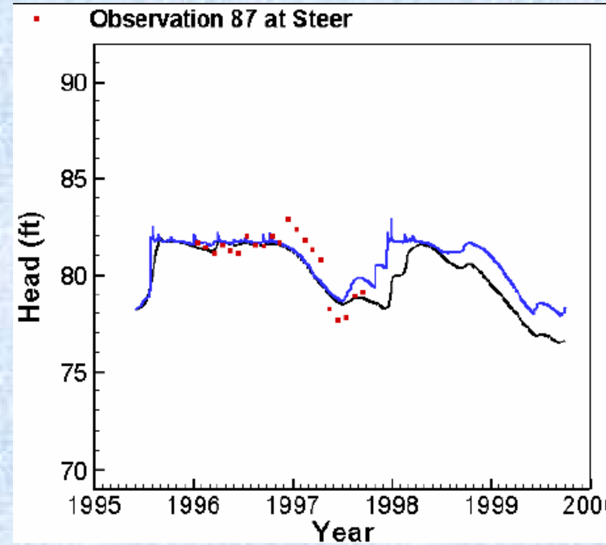
89-96 Stream Flow (8)

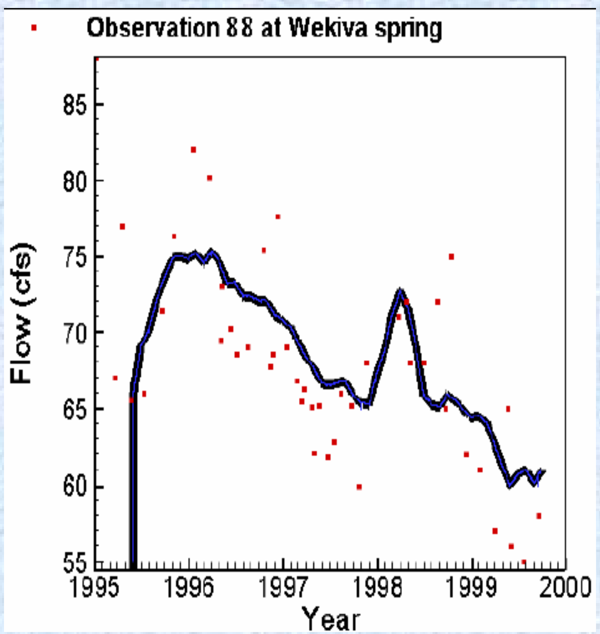


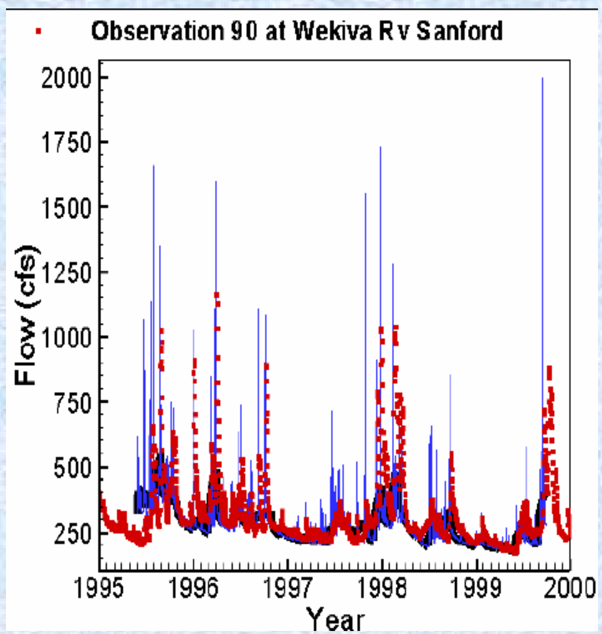
Results for Daily vs. Monthly Rainfall

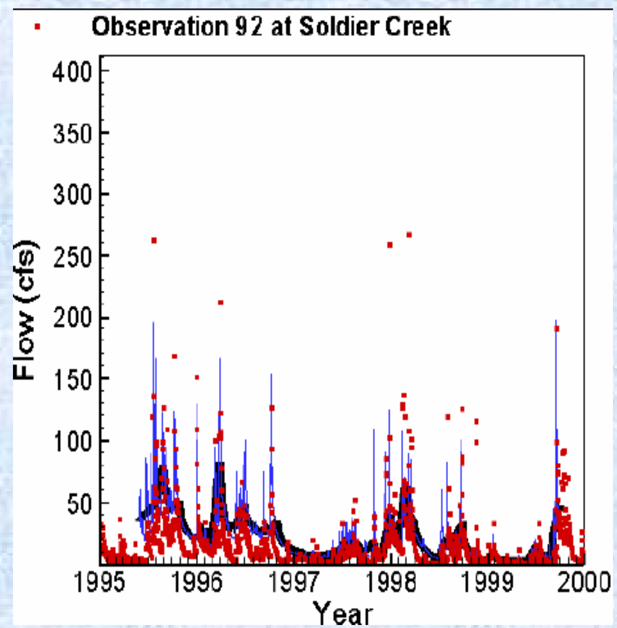




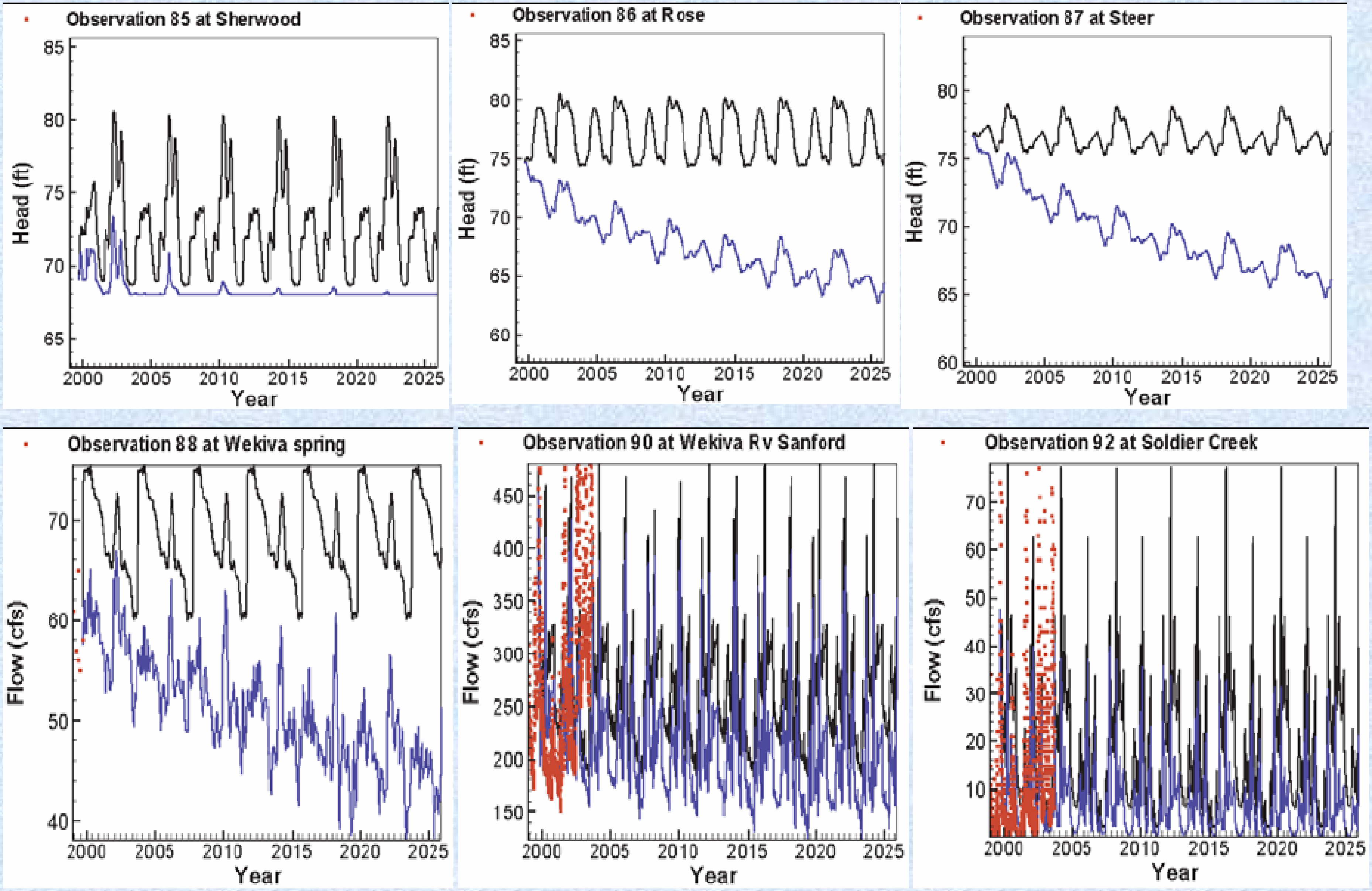








Results for Higher Floridan Pumping



Computation Run-times – On Pentium IV, 2000 MHz

- June 1995 through September 1999 with daily precipitation fluctuation – 14 days
- June 1995 through September 1999 with monthly averaged precipitation fluctuation – 3 days
- September 1999 through September 2025 with monthly averaged precipitation fluctuation – 16 days
- NOTE: Today's Pentium machines are at least twice as fast.
- NOTE: Richard's Equation solution (and to some degree physics based ET) provide greatest numerical difficulties

Strengths vs weaknesses for potential KB application

- Holistic approach for multi-scale objectives
- Incorporates general structures and rules of operation
- Flexibility of formulation to adapt to problem objectives and available data
- Adaptive time-stepping for large rapid events
- Rigorous formulation that does not ignore convergence of simulation between domains
- Complex data processing and manipulation
- Diffusion wave neglects inertial effects

Proposed model implementation strategy for the Kissimmee Basin

Data Needs

- Elevation data
- Rainfall data
- LAI, RD, ET_P

- USGS NED or higher resolution project data if available
- Can use NEXRAD data or SFWMD data and Thiessen polygon or SFWMD TIN approach
- Can use existing MIKE SHE database, USGS data, SFWMD data, and/or literature values

Data Needs

- Overland roughness coefficients
- Canal Cross-sections
- Canal roughness coefficients

- SFWMD land-use based Manning's data
- Can use available HEC-RAS and MIKE 11 cross-sections
- Can use values from calibrated HEC-RAS, MIKE 11, and AdICPR models or literature values

Data Needs

• Canal network	• Can use available existing HEC-RAS, MIKE 11, and AdICPR networks and GIS coverages (ArcHMS)
• Structure protocols	• Can use logic in existing HEC-RAS, MIKE 11, and AdICPR files and SFWMD/USACE rules
• Canal boundary conditions	• Use available data from DBHYDRO

Data Needs

- Unsaturated Hydraulic Parameters
- Can used existing MIKE SHE database or UofF Soil Database if solving Richard’s Equation
- Hydrostratigraphy
- Can use data from existing MODFLOW and MIKE SHE models, USGS studies, SFWMD studies, and any available county studies.
- Saturated Hydraulic Parameters
- Can used existing MIKE SHE and MODFLOW files and available surficial aquifer data
- Representation of sinkholes
- Can rely on available understanding of connection of karst features wit the SAS, ICU, and FAS

Data Needs

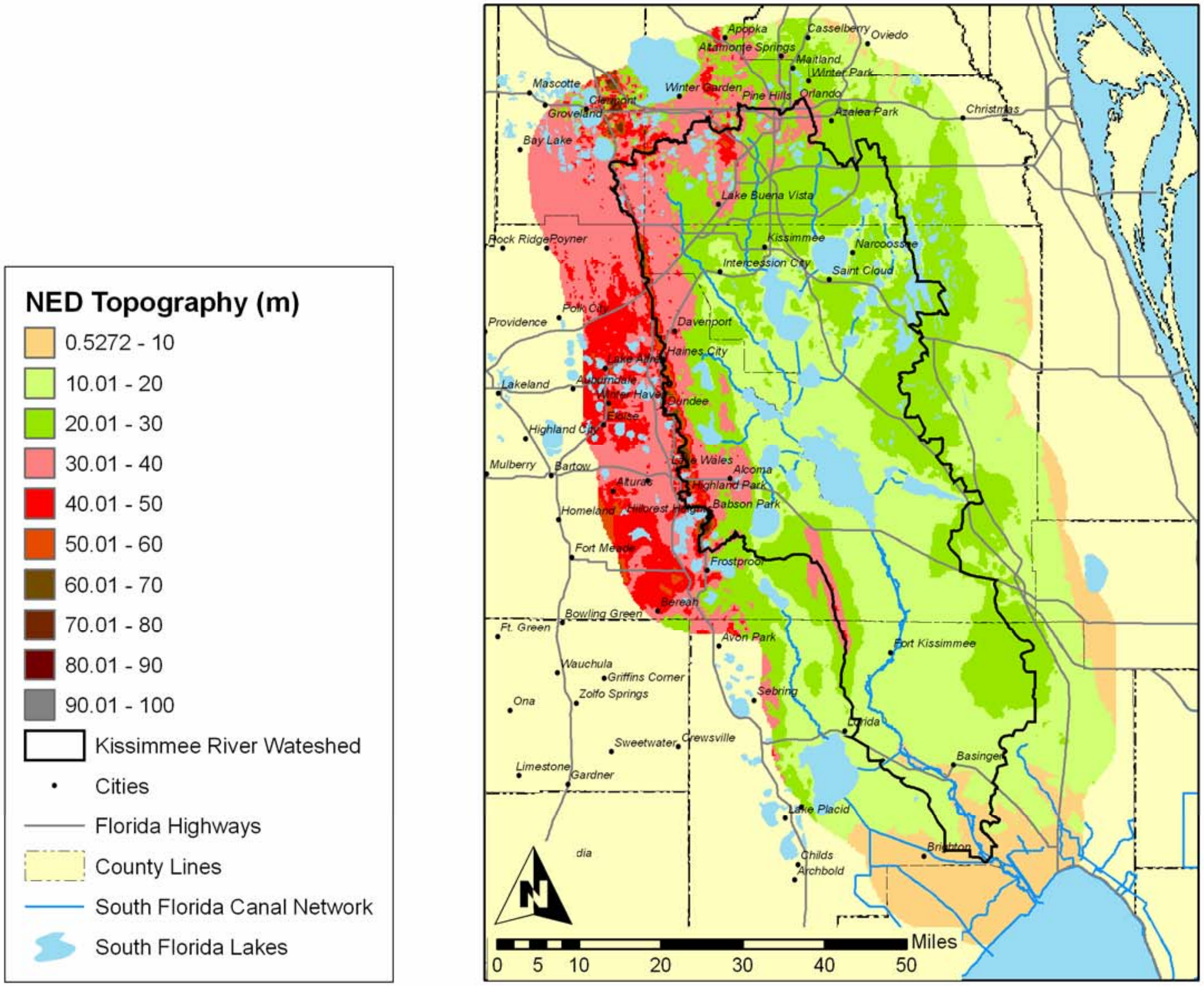
- Saturated Zone Boundary Conditions
- Can use no-flow for surficial aquifer at surface water basin boundary

- Saturated Zone Pumping Rates
- Can use available SFWMD data

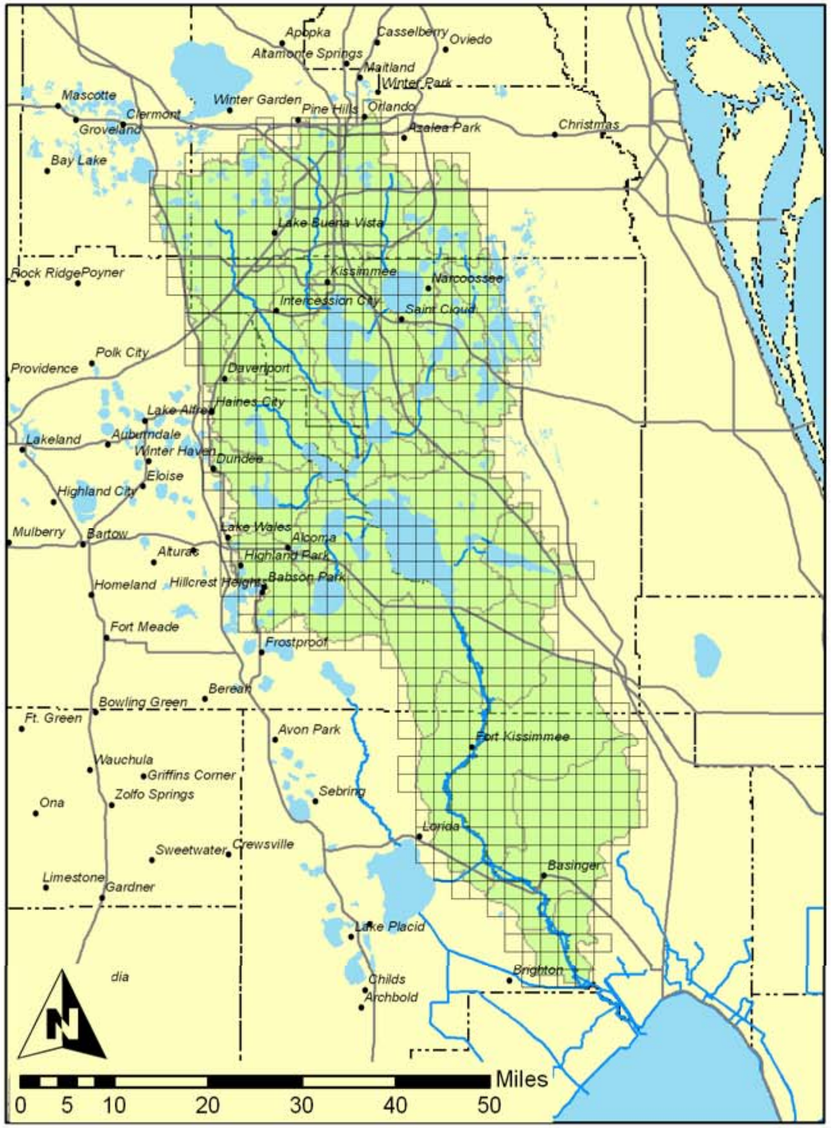
- Canal Abstractions (if present)
- Can use available SFWMD data

- Irrigation areas, rates, etc.
- Can use available SFWMD data and MIKE SHE irrigation database and results

Basin Delineation



Grid Size



10,000 ft Grid Spacing

Kissimmee River Subbasins

Cities

Florida Highways

County Lines

South Florida Canal Network

South Florida Lakes

Discretization Assumptions for run-time calculations

- Unsaturated Zone response needs to be explicitly modeled using the Richard’s equation formulation
- The Floridan aquifer system can be modeled as a simple head-dependent flux boundary condition

Grid Size

Grid Size (ft)	No. Columns	No. Rows	No. Active Cells
500	~ 550	~986	~252,636
1000	275	493	63,159
2000	~ 138	~ 247	~15,790
5000	~ 55	~ 99	~2,527

Example Run Times

Model	Notes	No. Active Cells	CPU Speed	Approximate Run Time (hrs/yr)
Mobile Bay	Pseudo soil functions, very detailed		~1 GHz	55
WOSC	Richard's Equations, daily rainfall	~180,000	~2 GHz	78
WOSC	Richard's Equations, avg. monthly rainfall	~180,000	~2 GHz	17
WOSC	Richard's Equations, avg. monthly rainfall	~180,000	~2 GHz	15

Estimated Run Times

Grid Size (ft)	Col, Row, Layers	No. Active Cells	Approximate Run Time (hrs/yr) 3 GHz
500	~ 550, 986, 4 (+1 OL)	~1,263,180	~76
1000	275, 493, 4 (+1 OL)	315,795	19
2000	~ 138, 247, 4 (+1 OL)	~78,950	~5
5000	~ 55, 99, 4 (+1 OL)	~12,635	~1

Model development and calibration

Task	**Conceptual Models**	**Detailed Models**
Data assimilation/ model development	2 weeks to several months	3 to 4 months
Calibration	weeks to months	3 to 4 months
Scenarios	days	days to weeks

Optimization

- Non-proprietary input and output files permit interfacing with PEST for parameter estimation, sensitivity analyses, uncertainty analyses, and optimization
  - *A interface between MODHMS and stand-alone optimization package was developed for SJRWMD*
  - *UCODE or PEST could be used to optimize operation rules for KRB*

Conclusions

- MODHMS has been successfully applied in similar regions of Florida
- MODHMS could be applied to the KRB in conceptual and detailed applications
- MODHMS has a rich set of options that would allow the model development to be tailored to the problem and aggressive project schedule
- MODHMS can deal with rainfall, ET, runoff, canal-aquifer interactions, surface-subsurface exchange, and flooding in a natural manner using a mass-conservative physics-based approach

Conclusions

- The level of detail in the detailed model(s) must be consistent with the project schedule and may require an iterative approach during model development
- Recommend applying MODHMS using the psuedo-soil functions
- Recommend calibrating the detailed model(s) using a coarse discretization (≥2000 ft) and using a final discretization of ~1,000 ft
- It may be possible to use PEST or UCODE to optimize KRB operation/management rules (the non-proprietary format will facilitate this)

Discussion